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Progress Report No. 6

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September 1, to November 30, 1961

THE SAMPLING OF AEROSOLS IN A TURBULENT AIR FLOW

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Prepared by: V. Goldschmidt

November 30, 1961

SYRACUSE UNIVERSITY RESEARCH INSTITUTE

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Prepared by: V. Goldschmidt

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Approved: S. Eskinazi
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I. ABSTRACT

The application of a hot wire anemometer as a sampling device for a dibutyl phthalate aerosol was found to be reliable. The count obtained by particles impacting on the heated filament in laminar flows showed a direct correlation to the concentrations measured by two other means.

In the runs conducted counts as high as 1000 counts per second per inch of wire length were noted and it was estimated that all drops above 3 to 5 microns were counted. With proper filtering of undesirable noise and slight improvements on the present set-up, the size of droplets to cause a countable signal will be lowered, and the application of the instrument hence broadened, improved, and then extended to turbulent streams.

An analysis is shown perturbing the equations of motion for an aerosol in air, attempting to arrive at the important Reynold's type equations. The resulting differential equation has both Lagrangian and Eulerian terms which do not immediately yield the corresponding correlating terms.

II. THE HOT WIRE ANEMOMETER

A wire heated to a mean temperature θ_w placed in a stream at mean temperature θ_o will be cooled by the stream itself and by the aerosol droplets, also at temperature θ_o, which come in contact with it. If this sensing wire is heated by a constant current, the fluctuations in the cooling effect of the stream caused by its turbulence and the instantaneous cooling due to the droplets will cause variations in the wire temperatures and hence changes in the resistance of the wire. These resistance changes will in turn cause changes in the voltage of the constant current heating the wire.

By amplifying the voltage variations due to the cooling effects, both from turbulence and the aerosol droplets, and discriminating these either by their amplitude or frequency, a count of the impactions on the wire anemometer can be made.

A block diagram of the instrumentation used is shown in Fig. 1. The tungsten wire used had a diameter of .00018" and a sensitive length of .068". The small tungsten filament was part of one of the legs of a Wheatstone bridge, which being initially balanced when the aerosol was not being injected in the wind tunnel, give a signal or detector voltage proportional to any resistance change in the heated filament.

The heat per unit time transferred from the wire to the air stream, with no aerosol, is given as

$$a\pi d\ell \quad (\theta_w - \theta_o)$$

where

a = heat transfer coefficient

d = wire diameter

ℓ = wire length

θ_w = temperature of wire

θ_o = undisturbed stream temperature

For thermal equilibrium then,

$$I^2 R_w = a \pi d \ell \ (\theta_w - \theta_o) \tag{1}$$

where

I = current flow through the wire

R_w = resistance of the wire at operating temperature

The heat transfer coefficient can be empirically related to Prandtl Number and Reynold's number, and these in turn can be lumped into the following form:

$$I^2 R_w = (A + B\sqrt{U}) \frac{R_w - R_o}{R_o} \tag{2}$$

The constant A is directly proportional to the length ℓ, and inversely proportional to the temperature coefficient of electric resistivity, α, of the wire, whereas the constant B is proportional to the square root of the wire diameter as well as directly proportional and inversely proportional to α. The constants A and B are usually obtained empirically for known velocity levels. A detailed derivation of the above relationship can be obtained in "Turbulence" by J. O. Hinze (McGraw-Hill).

When exposed to turbulent, or fluctuating air flow, the wire will have a change in resistance whose value can be based on the given thermal equilibrium relationship.

The total stream velocity U can be broken up into a mean velocity $\bar{U}$ and a fluctuating component u. The resulting wire resistance R_w can be similarly interpreted as composed of a mean value $\bar{R}_w$ and a change or offset from the mean value, r_w. The mean values will be related as

$$I^2\bar{R}_w = (A + B\sqrt{\bar{U}})\frac{\bar{R}_w - R_o}{R_o} \tag{3}$$

In order to find the relationship between u and r_w we substitute in Eq. (2) to obtain:

$$I^2 (\bar{R}_w + r_w) = (A + B\sqrt{\bar{U} + u})\ \frac{\bar{R}_w + r_w - R_o}{R_o}$$

If in addition to the small cooling caused by the fluctuating turbulence, we consider the impactions of a droplet of mass m and specific heat c_p', then, if $\dot{m}$ is mass per unit time,

$$I^2 (\bar{R}_w + r_w) = (A + B\sqrt{\bar{U} + u})\frac{\bar{R}_w + r_w - R_o}{R_o} + \dot{m}c_p' (\theta_w - \theta_o)$$

But

$$\theta_w - \theta_o = \frac{R_w - R_o}{\alpha R_o}$$

so then

$$I^2 (\bar{R}_w + r_w) = \left[(A + B\sqrt{\bar{U} + u}) + \frac{\dot{m}c_p'}{\alpha}\right]\frac{\bar{R}_w + r_w - R_o}{R_o}$$

for $\bar{R}_w - R_o \gg r_w$ and $\bar{U} \gg u$, and using Eq. (3), the above simplifies to

$$- I^2 r_w = \left(\frac{Bu}{2\sqrt{\bar{U}}} + \frac{\dot{m}c_p'}{\alpha}\right)\varphi^2 \tag{4}$$

where φ = overheat ratio = $\dfrac{R_w - R_o}{R_o}$.

The voltage fluctuations due to the combined effects of turbulence and droplet impactions will be given as

$$e = I_{rw} = - S_1 u - S_2 \dot{m} \tag{5}$$

where the coefficients S_1 and S_2 can be considered as sensitivities, given as:

$$S_1 = \frac{B\,\varphi^2}{2I\sqrt{\bar{U}}} \qquad S_2 = \frac{c'_p}{\alpha I}\,\varphi^2$$

It is desirable to make S_2, as well as the ratio S_2/S_1 large. As

$$S_2 = \frac{c'_p\,(\varphi)^2}{\alpha I} \quad ,$$

and

$$\frac{S_2}{S_1} = \frac{c'_p\,2\sqrt{\bar{U}}}{\alpha B} \quad \alpha \quad \frac{c'_p}{\ell}\sqrt{\frac{\bar{U}}{d}} \quad ,$$

as it was found that B was proportional to the square root of the wire diameter, as well as directly proportional to ℓ and inversely proportional to α. For larger overheat ratios and mean stream velocities, and smaller wire lengths, diameters and wire temperature coefficient of resistivity, the chances of discriminating the impactions from the turbulence will improve.

Using Eq. (3) it can be shown that

$$S_2 = \frac{c'_p\,(\varphi)^{3/2}\,(\bar{R}_w)^{1/2}}{\alpha[(A + B\sqrt{\bar{U}})]^{1/2}} \quad \alpha \quad \frac{c'_p\,(\varphi)^{3/2}\,(\varphi + 1)\,R_o}{(1+\text{const.}\sqrt{\bar{U}d})}$$

or if ρ = resistivity

$$S_2 \;\alpha\; \frac{\varphi^{3/2}\,(\varphi + 1)\,\rho}{d^2(1+\text{const.}\sqrt{\bar{U}d})}$$

which shows that S_2 is independent on wire length but increases with overheat ratio, resistivity and decreases very fast with wire diameters.

The detected voltage on the wheatstone bridge is compensated for the thermal lag caused by the wire and simultaneously amplified by a compensation amplifier as described in Ref. 2. The low frequencies of the signal are then filtered with an RC filter and the filtered signal is in turn fed into a Tektronix Type 533 Oscilloscope with a Type B Plug-in-Unit set at a magnification of 1 volts/cm. A Hewlett Packard Type 521E electronic counter was adjusted so variations in voltage above .028 volts in the amplified signal would cause a count. The electronic counter, in addition to an input sensitivity adjustment with a continuous adjustable sensitivity from .2 volts rms to 100 volts rms also has gating times of 1/10, 1 and 10 seconds. In the runs so far performed the gating time was set at 10 seconds. The range of the counter is specified as 1 cps to 120 kilocycles; blips as close as 8×10^{-6} seconds would hence still be counted.

In future studies the use of a constant temperature type of hot wire anemometer is to be investigated. A constant temperature anemometer does not require compensation and might give a more distinct signal.

III. TEST PROCEDURE

The output from a DeVilbiss constant flow type 841 Nebulizer was introduced into a small wind tunnel shown in Fig. 2. The mean velocity at the exit of the wind tunnel was of 11'/sec. and the cross section at the exit mouth was of 1.96 inches in diameter.

The aerosol was introduced into the wind tunnel at a steady rate, and upon also reaching steady output conditions at the tunnel mouth the following measurements and samples were taken.

1) With a fixed over-heat ratio on the hot wire placed in line with the axis of the tunnel, the impactions recorded by the counter were noted for at least 10 counts as obtained with a gate time of 10 seconds. The difference in between successive readings rarely exceeded 10 percent, so the deviation in the mean count was well under 5 percent. The orientation and location of the hot wire were found not to be critical in the count and the probe was hence placed by eye at approximately the same position from run to run. The mean count obtained was furthermore found to be constant with time. It must be noted however that no runs were taken for more than thirty minutes and that the effect of aging on the wire has not yet been thoroughly investigated. Aging of the wire may be caused both by stretching and coating or oxidation. Stretching will cause an increase in the wire overall resistance, whereas a coating on the wire may cause a decrease in the overall resistance. Any changes in the wire resistance will affect the over-heat ratio and also the sensitivity to the impactions. In the runs taken the wire was kept in operation long enough so the counts obtained would yield a reliable average value which did not vary due to changes in the wire resistance for runs as long as thirty minutes in duration.

2) A device hereafter called "trapping cylinder" was built to permit the capture of a sample from the aerosol stream from which the mass mean diameter and concentration could be evaluated. As the name implies, the sampling device consists of a cylinder, Fig. 3, which may be oriented so the stream flows through it undisturbed until spring loaded covers are triggered. The covers, after being released, completely enclose a volume of the stream, and if the cylinder is immediately placed

in a vertical position, the aerosol will settle gravitationally on one of the covers which is conveniently made out of glass and can be removed after all the droplets have settled.

The terminal velocity of a 1 micron rigid sphere is of 3.49×10^{-3} cm/sec (Ref. 3 page 65). A 1 micron dibutyl phthalate drop, right below the top cover would then take less than an hour to settle on the glass slide if only gravity effects were acting on it. In all the samples collected settling times from three to five hours were allowed. The evaporation effects were still negligible and particles from one half a micron up had all settled when the glass slides were observed.

For the first runs measurements of density, or number of particles per unit area, on the slide were taken at different locations. Due to the acceleration force acting on the particles upon placing the trapping cylinder in a vertical position it was expected that some non-uniform density would result on the slide. It was found however that the variation in density was not dependent on the location of the slide, except, of course, for a narrow width along the edge of the circular glass piece. Sufficient pictures and observations were then made to obtain a reliable measure of mass mean diameter and aerosol concentration. A typical photograph of the sample collected is shown in Fig. 4. In the determination of aerosol concentrations through the wind tunnel it was assumed that the number of particles clinging onto the walls of the trapping cylinder was negligible when compared with the number of particles settling on the glass slide itself. In all cases the glass slide was cleaned with alcohol rinsed with water and polished with Laboratory Aerosol Solution prior to sampling.

3) The third method used to determine the concentration and number of particles of dibutyl phthalate flowing through the tunnel was to sample isokinetically through a Gelman 1/4" diameter isokinetic probe. Type AM-4 Gelman Polypore filter pads, 2" diameter were used. Samples were collected by isokinetically sampling during four different lengths of time, in between 20 and 120 seconds. The collected samples were first dissolved in alcohol and then treated with sodium carbonate and diazo-benezene sulfonic acid which gave a color depending on the amount of β-naphthol tracer and hence also dibutyl phthalate collected. By comparing with standard solutions the corresponding aerosol concentrations in the stream can be calculated as the average of the values obtained based on each one of the four collected samples. Through some initial checks it was found that there was no considerable amount of dibutyl phthalate leaking through the filter pad. The flow through the probe was adjusted so that sampling as close to isokinetic as possible was undertaken. The possible deposits of dibutyl phthalate on the walls of the probe were neglected. With sampling times above 30 seconds it is justifiable to consider the error introduced by neglecting the deposits on the wall as a small amount.

IV. TEST RESULTS

With a wire .068" in length, an overheat ratio of 0.4, and sensitivity of the counter and amplifiers set so voltage variations above .028 volts caused a count, nine runs were performed for which the following data was obtained.

a) Average number of counted impactions on the wire for a ten second interval.

b) Mass mean diameter of the collected sample and number of particles within a size interval collected on the glass slide.

c) Amount of aerosol, in grams, collected through the probe per unit time. By assuming a mass mean diameter as given above the number of particles flowing into the probe per unit time may be evaluated.

Table I shows the results obtained for runs 17 through 25. Runs 1 through 17 were done with different wire lengths and different electronic set-ups and do not give a direct correlation with the tabulated values.

A visual observation of Fig. 4 will show that the size distribution, even though it will tolerate a relatively good estimate of the mass mean diameter, does not easily give a total number of particles flowing through the wind tunnel. It was chosen to define instead the distribution on the glass slide as the number of particles above a given droplet diameter d. The curves shown in Figs. 9 through 17 describe the distribution and number of particles collected on the total slide. The corresponding number of particles through the wind tunnel can be calculated by knowing the depth of the trapping cylinder and the exit diameter of the tunnel. Figures 5 through 8 show the size distribution curves for Runs 17 through 20. Based on their similarity, and the tabulated values of mmd on Table I, it appears justifiable to consider an average mass mean diameter of 5.78 microns. (Note, the volume of a 5.78 micron particle is approximately 1×10^{-10} cubic centimeters.)

Known the mass mean diameter and the respective cross sectional areas of the isokinetic probe and the wind tunnel, from the collected samples in grams per unit time, the number of particles flowing through the wind tunnel per unit time can be calculated. It is expected then that the count on the hot wire anemometer will maintain some relationship with the number of particles flowing through the wind tunnel, as above obtained.

The relationship has been plotted in Fig. 18. The count on the hot wire anemometer has been reduced to counted impactions per minute, and the number of particles flowing through an area equal to the wire cross sectional area normal to the stream. If the coefficient of impaction of the wire were unity and every impaction were recorded, the relationship of the counted impactions per minute to the particles per minute per wire area would be as shown in the broken line of Fig. 18. Figure 18 does show, however, the reliability of the hot wire anemometer. The error in the count is linear with the concentration. This indicates that below a given size drop the resulting voltage was not sizable enough to give a count, and that furthermore this number of particles below which no count is recorded increases linearly with aerosol output which agrees with the noted similarity in size distributions for different runs (Figs. 5 through 8).

A further correlation can be made. An estimate of the number of particles with diameter large enough to cause a count flowing through the tunnel per unit time can be obtained from the count on the hot wire anemometer, provided 100 percent efficiency can be assumed. This number of particles can be related to the corresponding number which would have been collected on the glass slide had only those large enough to cause a signal been kept. With this quantity, the size below which no countable signal resulted, or "cut-off diameter" can be obtained from the curves in Figs. 9 through 17 for each one of the runs. The resulting cut-off diameters for runs 21 through 25 are shown in Table II.

Summarizing, we note that for various aerosol concentrations the hot wire anemometer showed a corresponding count which was directly related to the true concentrations. Inasmuch as the limitation of the device as to smallest particle to cause a signal has not been of concern, a cut-off diameter in the neighborhood of 3 to 5 microns was noted, assuming the impaction coefficient close to unity. Now that the reliability of the hot wire anemometer has been shown, its limitations and characteristics are to be evaluated.

V. DISCUSSION AND ANALYSIS

1. Coincidence of Impactions on the Hot Wire Anemometer Probe

With the present set-up one of the limitations of the hot wire anemometer is that of simultaneous or infinitely close impactions. The limiting component will be the electronic counter which will not respond to frequencies above 120 kilocycles. This will imply that impactions closer than 8×10^{-6} seconds will record only one count. In Run 25 the number of particles per wire area per minute was around 13000. At a stream velocity of 11'/second (or approximately 8×10^3 inches/min, this would imply that if all the particles were equally spaced and had a diameter equal to that of the mass mean, then there will be a flow of $13000/1.2 \times 10^{-5}$ or approximately 1×10^9 particles/minute per square inch, and a total of $1 \times 10^9/8 \times 10^3 = 1.25 \times 10^5$ particles/in^3. Each particle would then occupy 8×10^{-6} cubic inches and the mean distance in between consecutive particles, if equal spacing occurred, would be of .02

inches, or 2.5×10^{-6} minutes apart which is much larger than the value for which coincidence would cause an error in readings. For the particles to be 8×10^{-6} seconds apart a concentration larger than 5×10^{17} particles/in^3 would be necessary. It must be noted though that the above assumes point sampling and coincidence due to particles moving on the same path line. The possibility of coincidence in sampling along the length of the wire is not completely ruled out by the argument presented and can be evaluated by testing with wires of different lengths and comparing the results, or by knowing the arrangement the particles assume within the stream, both in laminar and turbulent flows.

2. Droplet Effects on Filament

The main purpose of the runs taken during this last period was to obtain a correlation and evaluate the validity of the hot wire anemometer as a sampling device. The phonomena of cooling by the droplets is caused by heat conducted to the drop at a lower temperature than the wire and by the impaction of the drop causing the wire to "swing" and hence be cooled by the stream itself. This latter aspect would allow this method of sampling to be applicable for solid aerosols as well as liquid aerosols. It is expected, however, that the cooling effect due to the droplet low temperature is of a much larger magnitude than that caused by the "swinging" of the wire.

During the runs reported an over-heat ratio of .4 was maintained. With a tunnel air temperature of 25°C and a temperature coefficient of electric resistivity of $5.2 \times 10^{-3}(°C)^{-1}$ it would imply a heated wire temperature of around 120°C. The boiling point of dibutyl phthalate is of 340°C, so it would seem rather improbable that the droplets are suddenly vaporized upon contact with the wire. Visual observations have been made to see what effects the wire has on the drops. With a 100 x magnification the following was noted. With the wire at room temperature the drops cling to the wire and group into larger drops evenly spaced along the wire in a bead-like arrangement. Upon heating the wire the drops were seen to rapidly decrease in size until they disappeared. As they became smaller they were not noticed to "roll off" nor to slide along the wire but remained in their original positions. The speed with which the drops travel doesn't allow their direct visual observation as they impact and flow past the wire. A spark source and photographic arrangement is being prepared to attempt to arrest the particles and observe their behavior. While the wire was heated no drops were noticed to cling on the wire but it appeared as if upon impaction they disappeared quite fast without being repelled by the wire.

A small increase in the cold resistance of the wire (10.37 to 10.60) was noted after a month and a half of testing. This slight increase could be caused by repeated stretching of the wire by the impinging droplets. The fact that the cold resistance has remained almost constant is encouraging however as it indicates that unless the stretching of the wire was such as to overshadow its effects on the wire resistance, there has been no significant coating by the dibutyl phthalate or the β-naphthol tracer.

3. Equations of Motion for Particles in Turbulent Streams

The hot wire anemometer is to be used as a sampling device in turbulent streams. Once its capabilities and limitations are well known for its behavior in laminar streams, it will be tested in streams with various degrees of turbulence.

The equations of motion of the suspended particles in a laminar flow were developed in Progress Report 1 and are now extended to turbulent flows.

Consider then a fluid stream of density ρ_f which moves at a velocity of $\vec{U}_f$ at any given point in the flow field. At the same corresponding points aerosol particles of density ρ_a and velocity $\vec{U}_a$ are considered. If $\vec{U}_f$ is steady and constant, eventually $\vec{U}_a$ will be equal to it; but when a change is made in $\vec{U}_f$, the velocity of the aerosol differs from that of the fluid. This change in velocity of $\vec{U}_f$ in general occurs due to turbulence and also due to the boundary configuration of the flow.

Considering first the aerosol particle, the forces acting on it are the fluid-pressure force, the viscous-drag and the gravitational force. This equation of motion of force for unit volume is:

$$\rho_a \frac{d\vec{U}_a}{dt} + \Delta p + \frac{\rho_f(U_a - U_f)}{d} (\vec{U}_a - \vec{U}_f)\ f \left[\frac{(U_a - U_f)d}{\nu}\right] - \rho_a\vec{g} = 0 \qquad (1)$$

For the fluid, investigating away from the solid boundaries the Euler's equation applies

$$\rho_f \frac{d\vec{U}_f}{dt} + \Delta p - \rho_f \vec{g} = 0 \qquad (2)$$

Combining these two equations, the pressure drops out.

$$\rho_a \frac{d\vec{U}_a}{dt} - \rho_f \frac{d\vec{U}_f}{dt} = (\rho_a - \rho_f)\ \vec{g} - \frac{18\mu}{d^2} (\vec{U}_a - \vec{U}_f) \qquad (3)$$

The last term in the right hand side of the previous equation is the drag on a sphere in the Stokes regime. Eq. (3) is a rather peculiar differential equation since it contains Lagrangian as well asEulerian terms. The velocity of the aerosol is a function of time only in the Lagrangian sense and therefore the acceleration has no space convective terms as the acceleration of the fluid. In order to be able to obtain correlation terms between the aerosol velocity fluctuation and that of the fluid stream, a different approach will have to be found, writing the equations of motion in terms of the relative velocity of the aerosol.

Since this approach is not available at the present time, Eq. (3) is still useful for deriving some valuable conclusions. Expanding Eq. (3) into its component form

$$\begin{aligned}
\rho_a \frac{du_a}{dt} - \rho_f \left[\frac{\partial u_f}{\partial t} + u_f \frac{\partial u_f}{\partial x} + v_f \frac{\partial u_f}{\partial y} + w_f \frac{\partial u_f}{\partial z}\right] &= \frac{18\mu}{d^2}(u_f - u_a) \\
\rho_a \frac{dv_a}{dt} - \rho_f \left[\frac{\partial v_f}{\partial t} + u_f \frac{\partial v_f}{\partial x} + v_f \frac{\partial v_f}{\partial y} + w_f \frac{\partial v_f}{\partial z}\right] &= \frac{18\mu}{d^2}(v_f - v_a) \qquad (4) \\
\rho_a \frac{dw_a}{dt} - \rho_f \left[\frac{\partial w_f}{\partial t} + u_f \frac{\partial w_f}{\partial x} + v_f \frac{\partial w_f}{\partial y} + w_f \frac{\partial w_f}{\partial z}\right] &= (\rho_a - \rho_f)g + \frac{18\mu}{d^2}(w_f - w_a)
\end{aligned}$$

Now if these equations are perturbed for the turbulent fluctuations, say for instance $u_a = \bar{u}_a + u'_a$ and $u_f = \bar{u}_f + u'_f$ and after substitution of these quantities in Eq. (3) and the time average is performed

$$\rho_a \frac{d\bar{u}_a}{dt} - \rho_f \left[\frac{\partial \bar{u}_f}{\partial t} + \bar{u}_f \frac{\partial \bar{u}_f}{\partial x} + \bar{v}_f \frac{\partial \bar{u}_f}{\partial y} + \bar{w}_f \frac{\partial \bar{u}_f}{\partial y}\right] - \rho_f \left[\frac{\partial \overline{u_f'^2}}{\partial x} + \frac{\partial \overline{u_f' v_f'}}{\partial y} + \frac{\partial \overline{u_f' v_f'}}{\partial z}\right] =$$

$$\frac{18\mu}{d^2}\left[\bar{u}_f - \bar{u}_a\right]$$

$$\rho_a \frac{d\bar{v}_a}{dt} - \rho_f \left[\frac{\rho \bar{v}_f}{\partial t} + \bar{u}_f \frac{\partial \bar{v}_f}{\partial x} + \bar{v}_f \frac{\partial \bar{v}_f}{\partial y} + \bar{w}_f \frac{\partial \bar{v}_f}{\partial z}\right] - \rho_f \left[\frac{\partial \overline{u_f' v_f'}}{\partial x} + \frac{\partial \overline{v_f' v_f'}}{\partial y} + \frac{\partial \overline{v_f' w_f'}}{\partial z}\right] =$$

$$\frac{18\mu}{d^2}\left[\bar{v}_f - \bar{v}_a\right]$$

$$\rho_a \frac{d\bar{w}_a}{dt} - \rho_f \left[\frac{\partial \bar{w}_f}{\partial t} + \bar{u}_f \frac{\partial \bar{w}_f}{\partial x} + \bar{v}_f \frac{\partial \bar{w}_f}{\partial y} + \bar{w}_f \frac{\partial \bar{w}_f}{\partial t}\right] - \rho_f \left[\frac{\partial \overline{u_f' w_f'}}{\partial x} + \frac{\partial \overline{v_f' w_f'}}{\partial y} + \frac{\partial \overline{w_f'^2}}{\partial z}\right] =$$

$$(\rho_a - \rho_t)g + \frac{18\mu}{d^2}\left[\bar{w}_f - \bar{w}_a\right] \tag{5}$$

According to these equations, the mean motion of the aerosol is affected by the mean motion of the fluid and the turbulent correlations of the fluid velocity fluctuations. These equations are then modified forms of the well known Reynolds equations.

One fact is certain and that is, if the gravitational settling is small, and if $\rho_a \gg \rho_f$, then since the acceleration of the particles is about the same magnitude as that of the fluid particle, the inertia terms of the fluid can be neglected. This indicates that the turbulent stress terms are just as unimportant as the mean fluid inertia terms. Thus if the above assumptions are justified Eqs. (5) reduces to the simple differential equation for the mean flow

$$\rho_a \frac{d\vec{U}_a}{dt} = \frac{18\mu}{d^2}(\vec{U}_f - \vec{U}_a) \tag{6}$$

4. <u>Thermal Repulsion and Impaction Coefficient</u>

The mass mean diameter of the droplets is of around 5 microns and the diameter of the wire used in our tests to date is just under 5 microns. A question immediately arises whether the usual concept of impaction coefficient, and if the assumptions of negligible thermal repulsion forces still hold.

In Progress Report No. 3 it was shown that the ratio of the inertia forces to the thermal repulsion forces for a 4 micron wire heated to

130°C, and droplets with a thermal conductivity around .002 cal/sec cm °C, is larger than 100. The conditions under which the reported runs have been tested agree with these assumptions and hence it is conservative to consider the thermal repulsion forces as negligible.

The impaction coefficient due to inertia has been studied by many experimenters. Some well known results are shown in Refs. (4) and (5). They have shown that the inertial impaction coefficient depends on the dimensionless ratio of the forces necessary to stop the particle in a distance equal to D, the diameter of the wire, to the drag forces acting on the particle. In the Stokes regime this ratio, ψ, becomes $\rho_p V d^2/18\mu D$ where ρ_p is the density of the aerosol and μ is the viscosity of the stream. For the conducted runs this ratio will be around 15. Langmuir and Blodgett (Eq. (42) show that the impaction coefficient, γ, will be given as

$$\gamma = \frac{4\,\psi}{4\,\psi + H} \tag{45}$$

where

$$H = 1 + .5708\left(\frac{C_D d}{48}\right) - .73 \times 10^{-4}\,(R_e)^{1.38}$$

C_D = drag coefficient and

R_e = Reynolds number based on the droplet diameter.

For the conditions of our runs, γ will then be around 96 percent.

As the ratio of the wire diameter to droplet diameter decreases towards unity, in addition to a contribution to the impaction coefficient from the inertia of the particles, there is an interception effect which becomes considerable. In this case, even though the center of the particle does not intersect the surface of the wire, it still passes close enough so impaction might occur. W. E. Ranz[6] discusses also the effects of the electrostatic attraction, settling and Brownian diffusion which might influence the coefficient of impaction for very slow streams and small collectors.

Landahl and Herrman[7] considered the inertia and interception effects additive and empirically obtained

$$\gamma = \frac{\alpha(\beta)^3}{a + \beta^2 + \alpha\beta^3} + \frac{d}{D}$$

where

$$\alpha = 400 \text{ cm sec/gram}$$

$$a = 3 \times 10^{-6} \text{ g}^2/\text{cm}^2\text{sec}^2$$

$$\beta = 18\mu\psi$$

The above relationship, even though it wasn't obtained for particles and collectors in the same size range as the hot wire and aerosol used in our tests, gives an approximate value of γ of 1.9 (190 percent).

W. E. Ranz, in his report prepared for the U. S. Atomic Energy Commission (Ref. 6), argues that the efficiency of impactions are not additive for separate mechanisms, but that a given mechanism may predominate at certain conditions. The interception effects become important when the ratio of the droplet to wire diameters approaches unity. Assuming an ideal potential flow around the cylindrical wire he showed that the coefficient of impaction γ will be near 1.5 when the ratio of the diameters is equal to 1.

Both Landahl and Herrman's and Ranz's results will imply that at the tested conditions an impaction coefficient around 190 percent or

150 percent will be closer to reality than the assumed 100 percent efficiency in Fig. 18 for the 1:1 response curve. It must be noted, however, that the cooling effect of a droplet touching the wire on a side will probably be less than that of a droplet hitting head on, unless every drop which touches the wire will wet it and completely surround it.

It is probable then that a correction factor on the impaction coefficient would be necessary to correct for errors in partial hits. These effects can be evaluated to some extent by testing with different wire diameters.

If the amount of cooling on the wire is independent on whether a droplet hits head on or on a side, a relationship between cut-off diameter and impaction coefficient can be obtained.

From Fig. 18, the percent of uncounted particles can be obtained for different impaction coefficients. If the slope of the full response curve is m_1, and that of the obtained count is m, then the percent of particles not counted would be

$$n = \left(\frac{m_1 - m}{m_1}\right) 100$$

For the tested conditions m is very close to .5, and the value of m_1 is known upon assuming a certain impaction coefficient. In turn, the cut-off diameter can be related to the percent of uncounted particles, known the distribution. Using the average distribution shown in Fig. 8b the following relationship would exist if every drop completely "wets" the wire, and "partial hit" effects would not be considerable.

Impaction Coefficient	Percent Uncounted (n)	Cut-off Diameter
100	50	3.5
125	60	4.0
150	66.7	4.4
175	71.4	4.7
200	75	5.0

The above certainly suggests a novel manner for determining the coefficient of impaction combining the interception effects and inertia effects. If the magnitude of the signal depends on the angle of hit, it is conceivable that its effect, as well as the actual cut-off diameter, could be directly obtained from measurements.

VI. CONCLUSIONS

In the past period the application of the hot wire anemometer as a sampling device has been shown to be possible and reliable. A direct correlation for the counted impactions on the wire and the actual concentration was noted. The limitations of the hot wire anemometer were discussed and will be evaluated in the following periods.

With these limitations as to "cut-off diameter" (or smallest drop to yield a countable signal), aging, coincidence and impaction effects known, the wire tested could be used to evaluate the diffusion and motion of an aerosol in a turbulent stream.

In the next period tests will be conducted, after obtaining a better filtering on the signal from the hot wire anemometer, to determine the limitations of the wire in its application as a sampling device. By testing with different over-heat ratios, different wire sensitive lengths and diameters, we will attempt to get insight as to the impaction coefficient, coincidence and partial hit effects.

TABLE I

Run Number	Count in 10 Seconds	M.M.D.	CC/Min. Thru Probe
17	107	6.2	.00023
18	86	5.7	.00025
19	137	5.7	.0004
20	284	7.5	.00125
21	583	4.5	.0023
22	382	4.3	.0018
23	474	6.6	.0024
24	610	6.5	.0029
25	712	5.4	.0036

TABLE II

Run Number	Cut-off Diameter, Microns*
21	2.8
22	3.4
23	5.3
24	5.6
25	4.8

Note: (Cut-off diameter was under 2 microns for runs 17 through 20.)

*Assuming 100 percent efficiency of impaction.

VII. REFERENCES

1. Hinze - Turbulence

2. Eskinazi, S., "An Investigation of Fully Developed Turbulent Flow in a Curved Channel," John Hopkins University Internal Flow Research Report I-20, Contract Nonr 248(33), August 12, 1954.

3. Green and Lane, "Particulate Clouds," Dusts, Smokes and Mists, D. Van Nostrand, 1957.

4. Sell, W., Forsuchungsheft 347, 1-22 (1931)

5. Langmuir, I., and Blodgett, K. B., Mathematical Investigation of Water Droplet Trojections, General Electric Report No. RL-225. July, 1945.

6. Ranz, W. E., The Impactions of Aerosol Particles on Cylindrical and Spherical Collectors, University of Illinois Engineering Experimental Station, March 31, 1959.

7. Landahl, H. D. and R. G. Herrman, Sampling of Liquid Aerosols by Wires, Cylinders and Slides and the Efficiency of Impactions of the Droplets, Journal of Colloid Science, Vol. 4, No. 2, April, 1949.

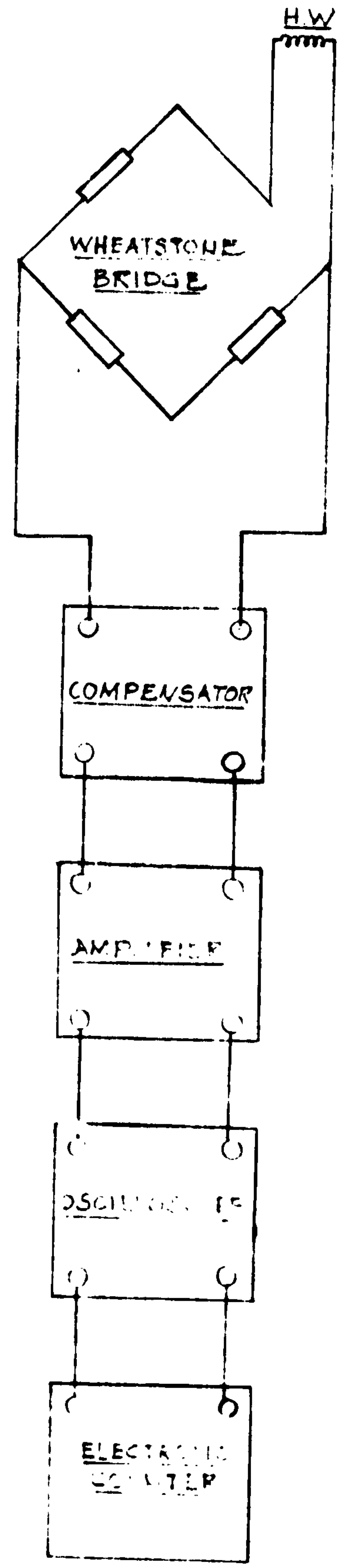


FIG.1 BLOCK DIAGRAM OF INSTRUMENTATION

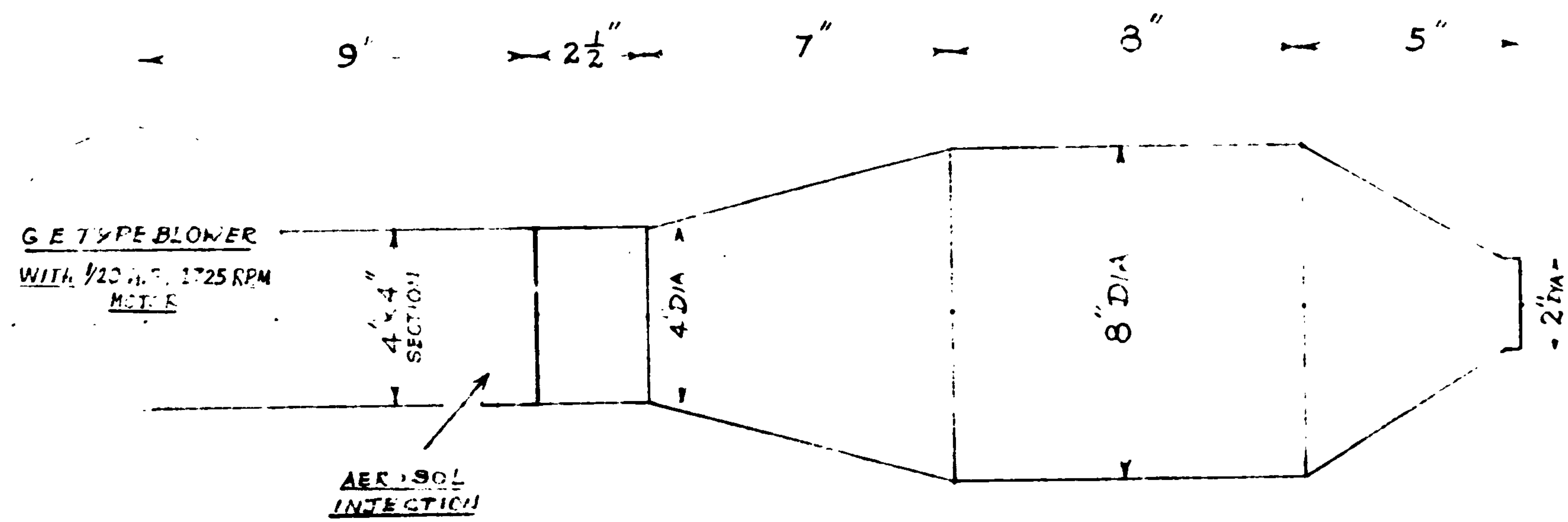
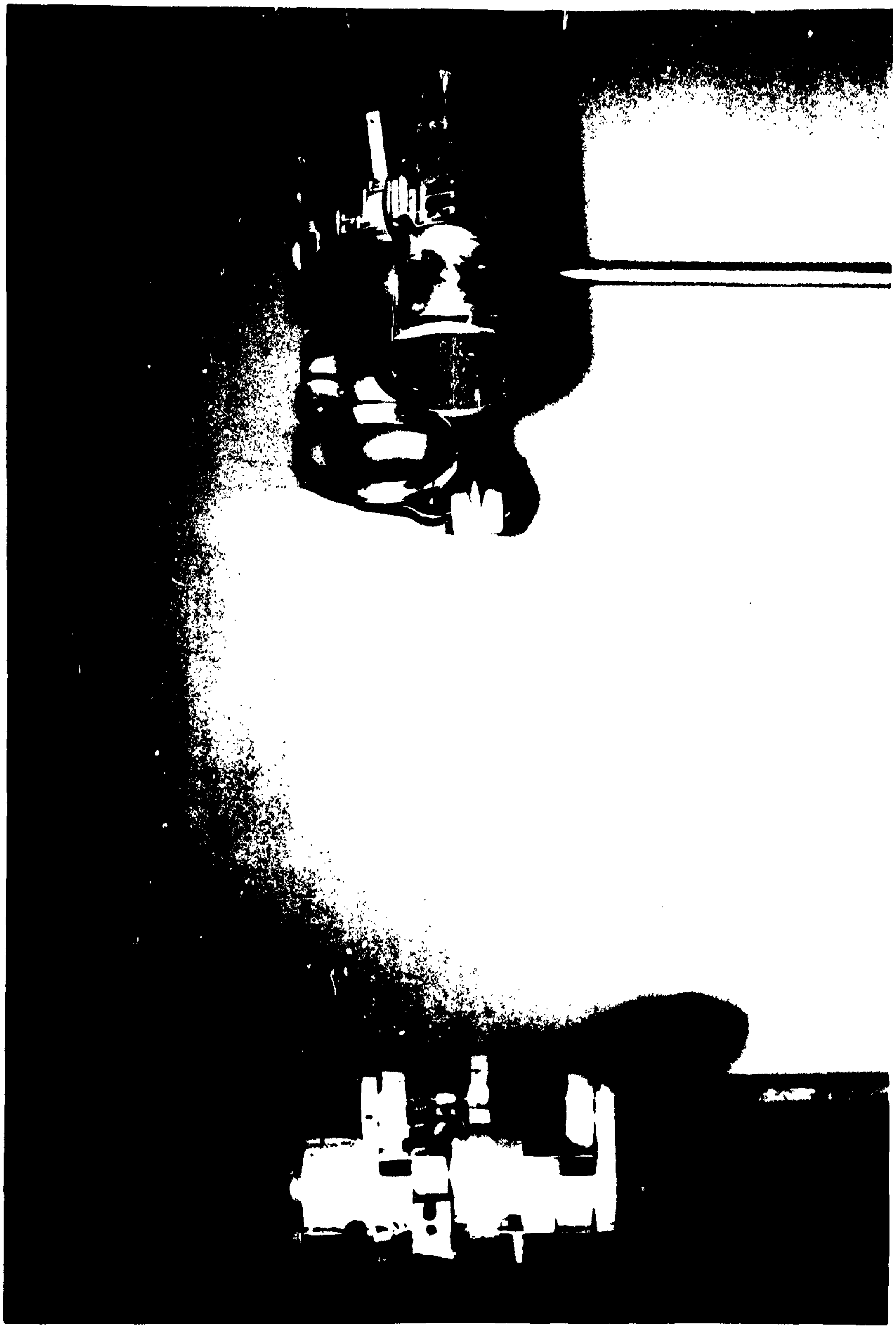


FIG. 2 WIND TUNNEL



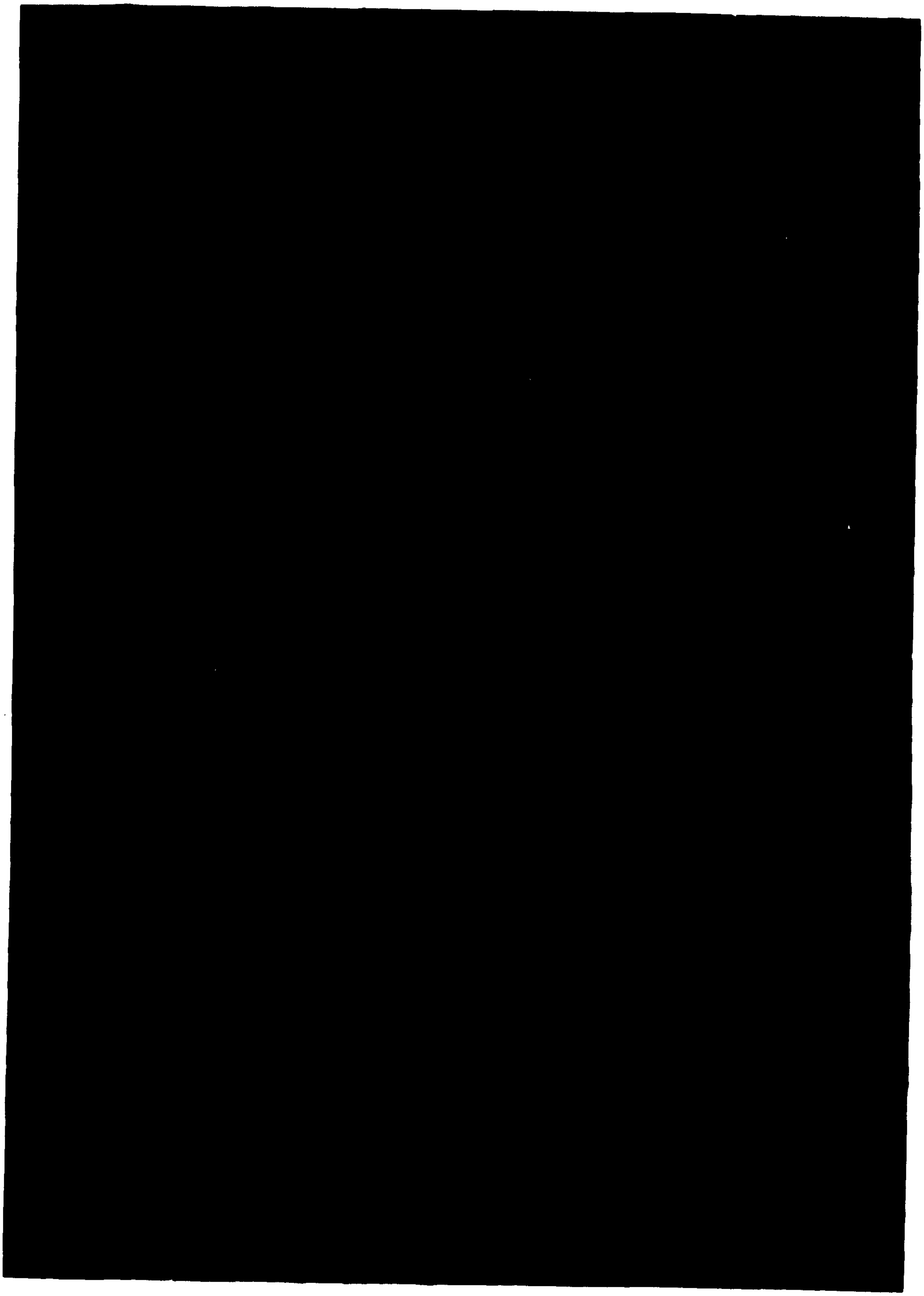


FIG 4

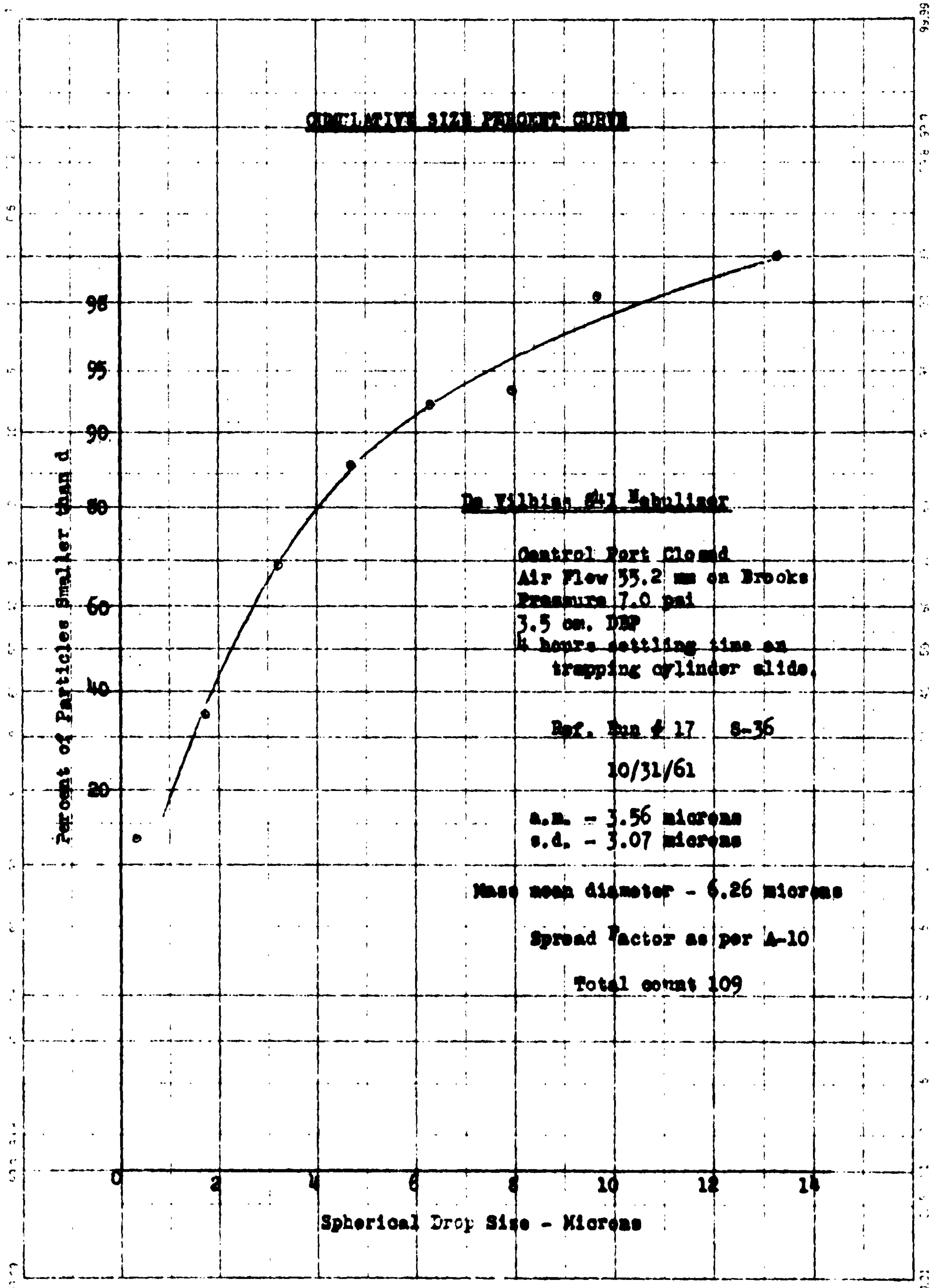

CUMULATIVE SIZE PERCENT CURVE
De Vilbiss #41 Nebulizer
Control Port Closed
Air Flow 55.2 mm on Brooks
Pressure 7.0 psi
3.5 cm. DEP
4 hours settling time on
trapping cylinder slide.
Ref. Run # 17 S-36
10/31/61
a.m. - 3.56 microns
s.d. - 3.07 microns
Mass mean diameter - 6.26 microns
Spread Factor as per A-10
Total count 109
Percent of Particles Smaller than d
98
95
90
80
60
40
20
0
2
4
6
8
10
12
14
Spherical Drop Size - Microns

Figure 5

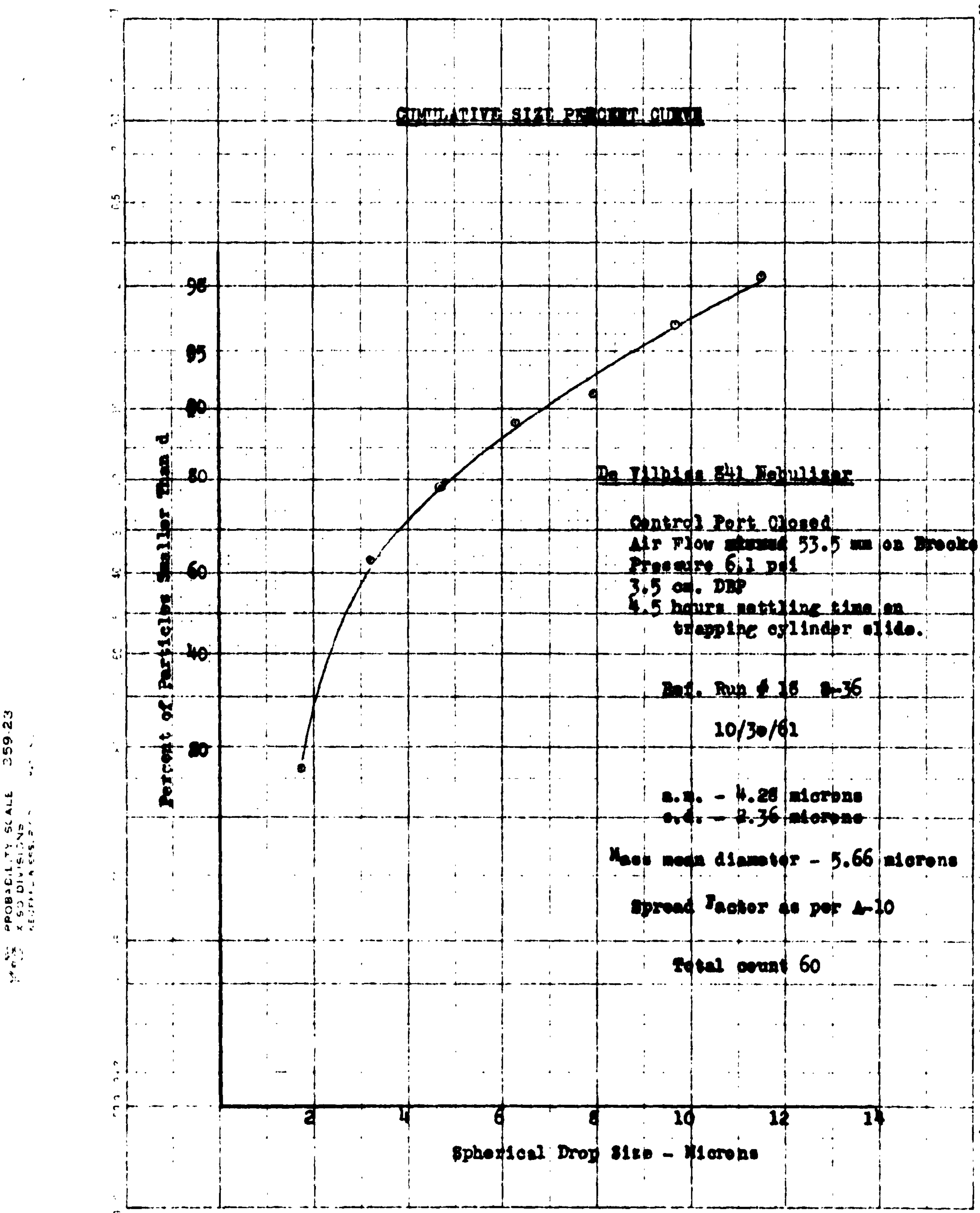
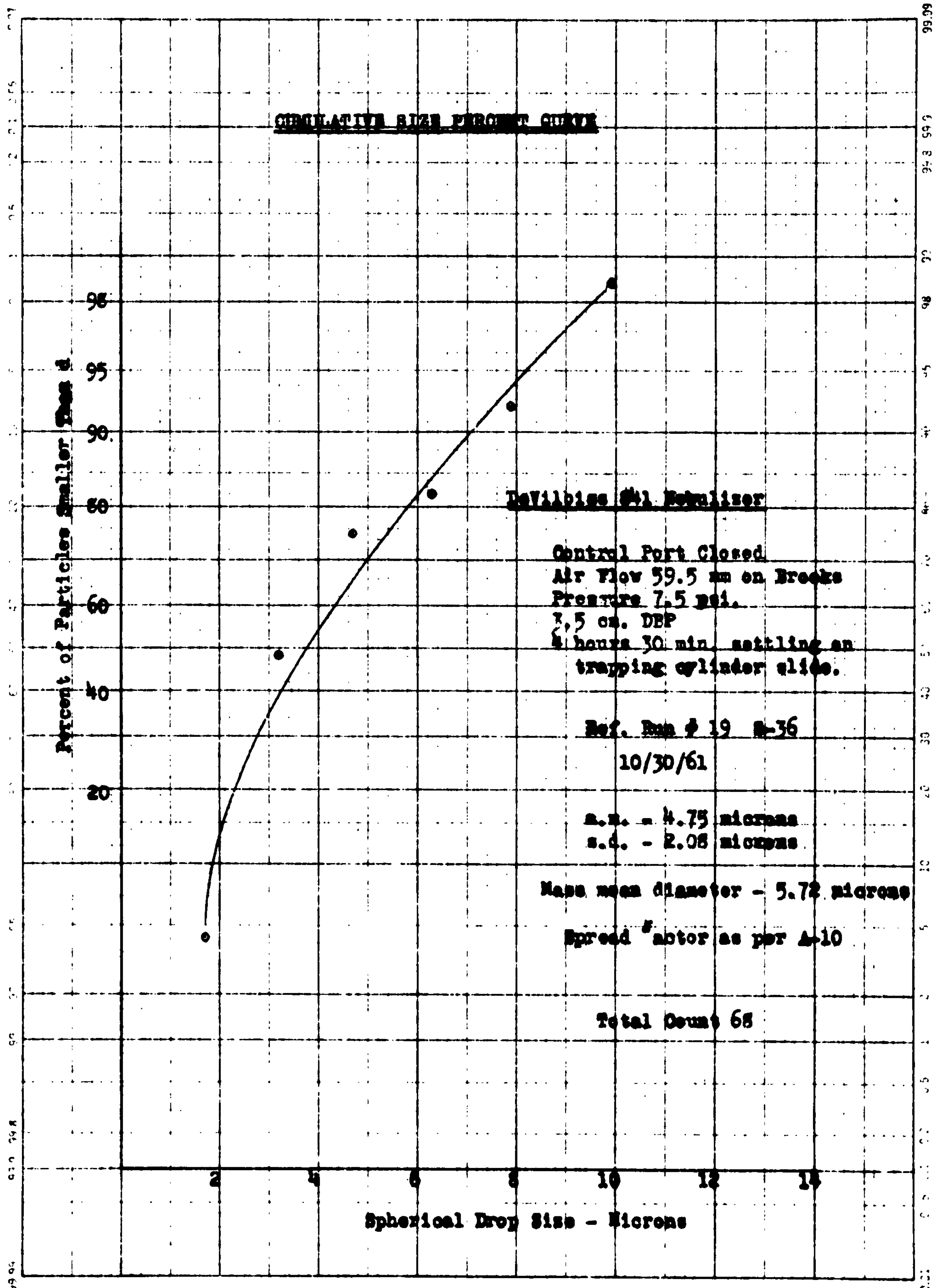

CUMULATIVE SIZE PERCENT CURVE
Percent of Particles Smaller Than d
98
95
90
80
60
40
20
De Vilbiss 841 Nebulizer
Control Port Closed
Air Flow 53.5 mm on Brooks
Pressure 6.1 psi
3.5 cm. DBP
4.5 hours settling time on
trapping cylinder slide.
Ref. Run # 16 B-36
10/30/61
a.m. - 4.28 microns
s.d. - 2.36 microns
Mass mean diameter - 5.66 microns
Spread Factor as per A-10
Total count 60
2
4
6
8
10
12
14
Spherical Drop Size - Microns
PROBABILITY SCALE 359.23
X 50 DIVISIONS

Figure 6



CUMULATIVE SIZE PERCENT CURVE
Percent of Particles Smaller Than d
98
95
90
80
60
40
20
DeVilbiss #41 Nebulizer
Control Port Closed
Air Flow 59.5 mm on Brooks
Pressure 7.5 psi.
4 hours 30 min. settling an
trapping cylinder slide.
10/30/61
s.d. - 2.08 microns
Mass mean diameter - 5.72 microns
Total Count 68
2
4
6
8
10
12
14
Spherical Drop Size - Microns

Figure 7

PROBABILITY SCALE 359-23
X 90 DIVISIONS
KEUFFEL & ESSER CO.

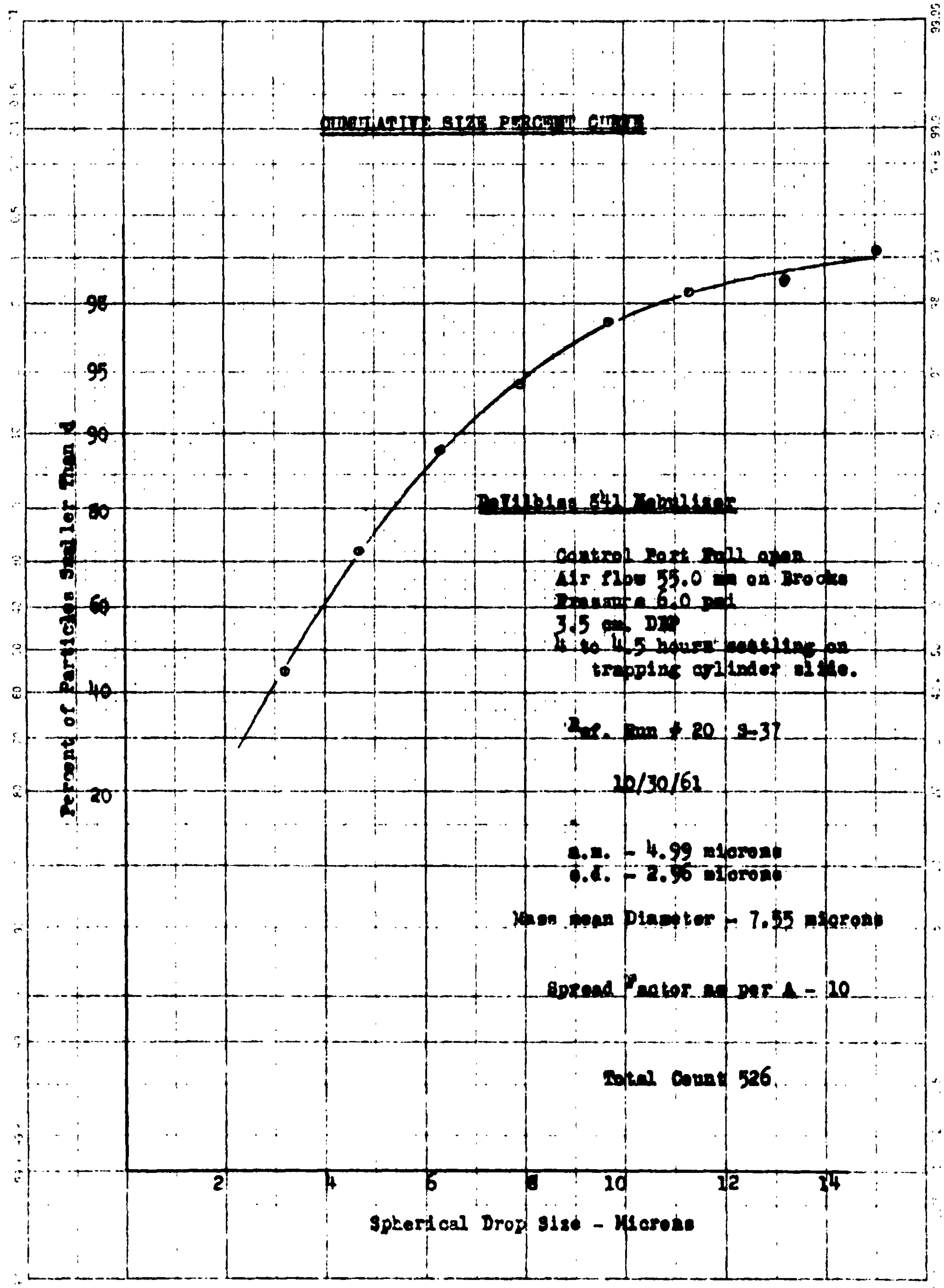
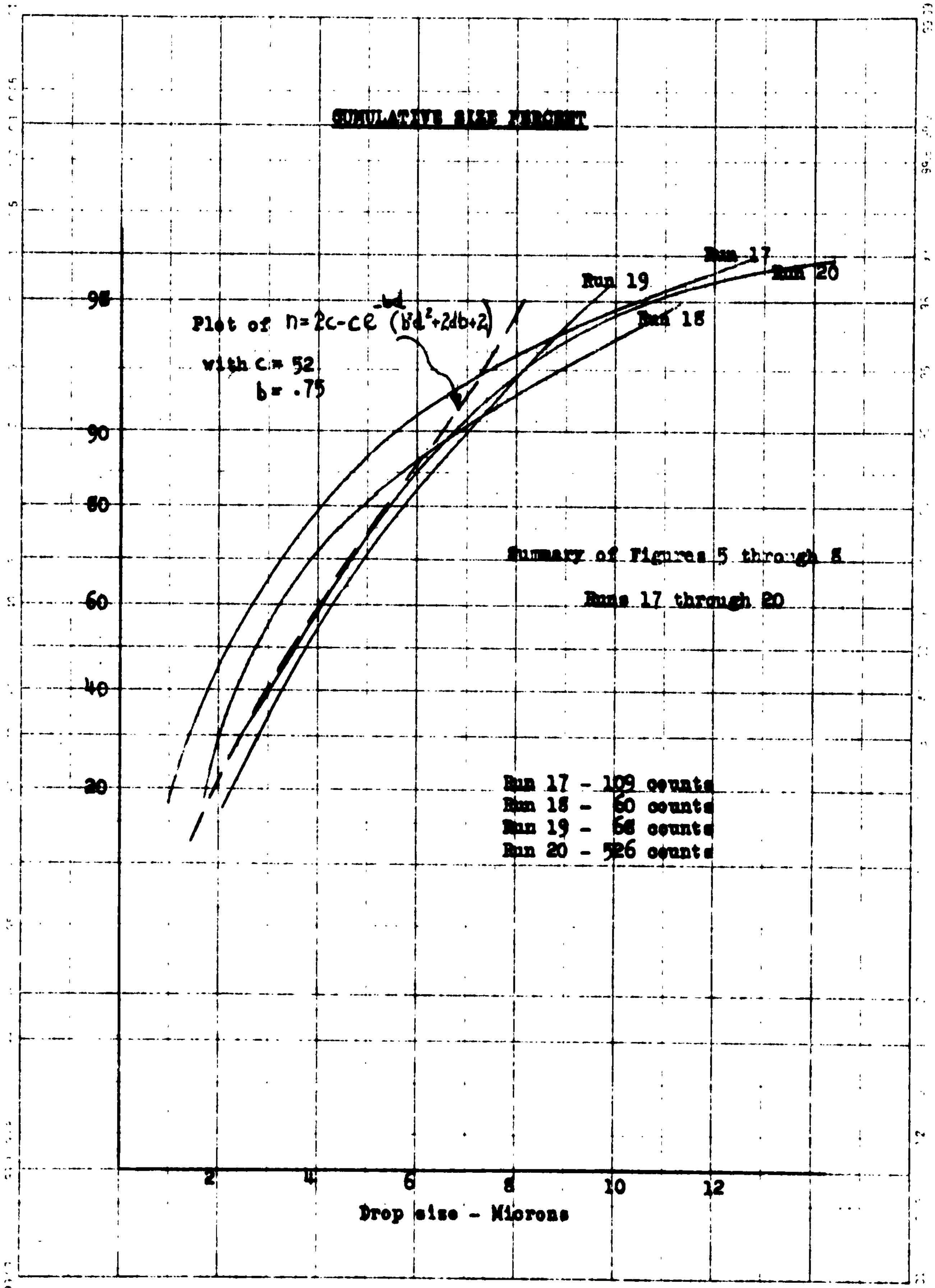
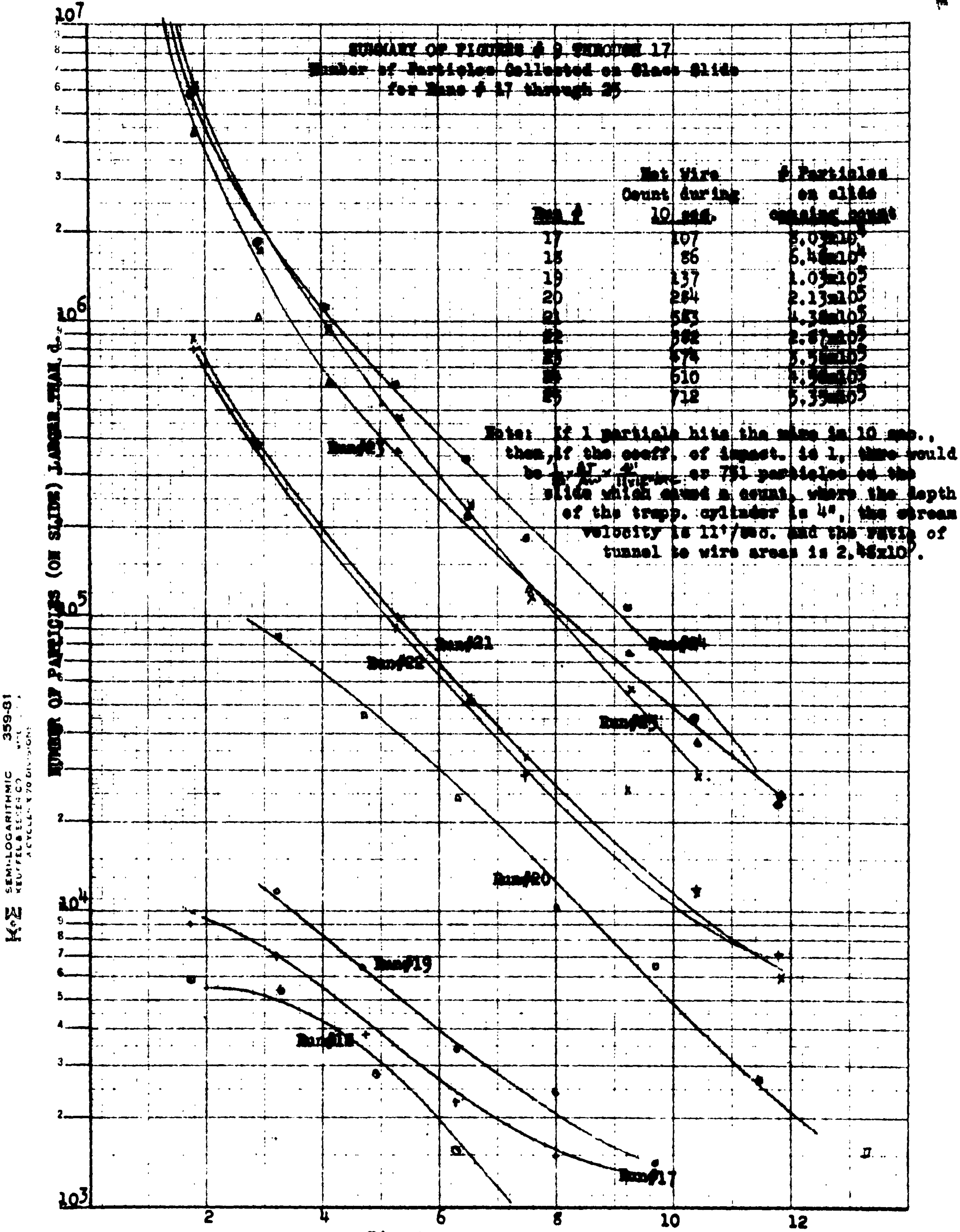


Figure 8



CUMULATIVE SIZE PERCENT
Plot of $n = 2c - ce^{-bd}(b^2d^2 + 2db + 2)$
with c = 52
b = .75
Run 17
Run 19
Run 20
Run 18
Summary of Figures 5 through 8
Runs 17 through 20
Run 17 - 109 counts
Run 18 - 60 counts
Run 19 - 68 counts
Run 20 - 526 counts
95
90
80
60
40
20
2
4
6
8
10
12
Drop size - Microns

Figure 8b



Diameter - microns   Figures 9 - 17

K-E 10 X 10 TO THE ½ INCH 359-11
KEUFFEL & ESSER CO.

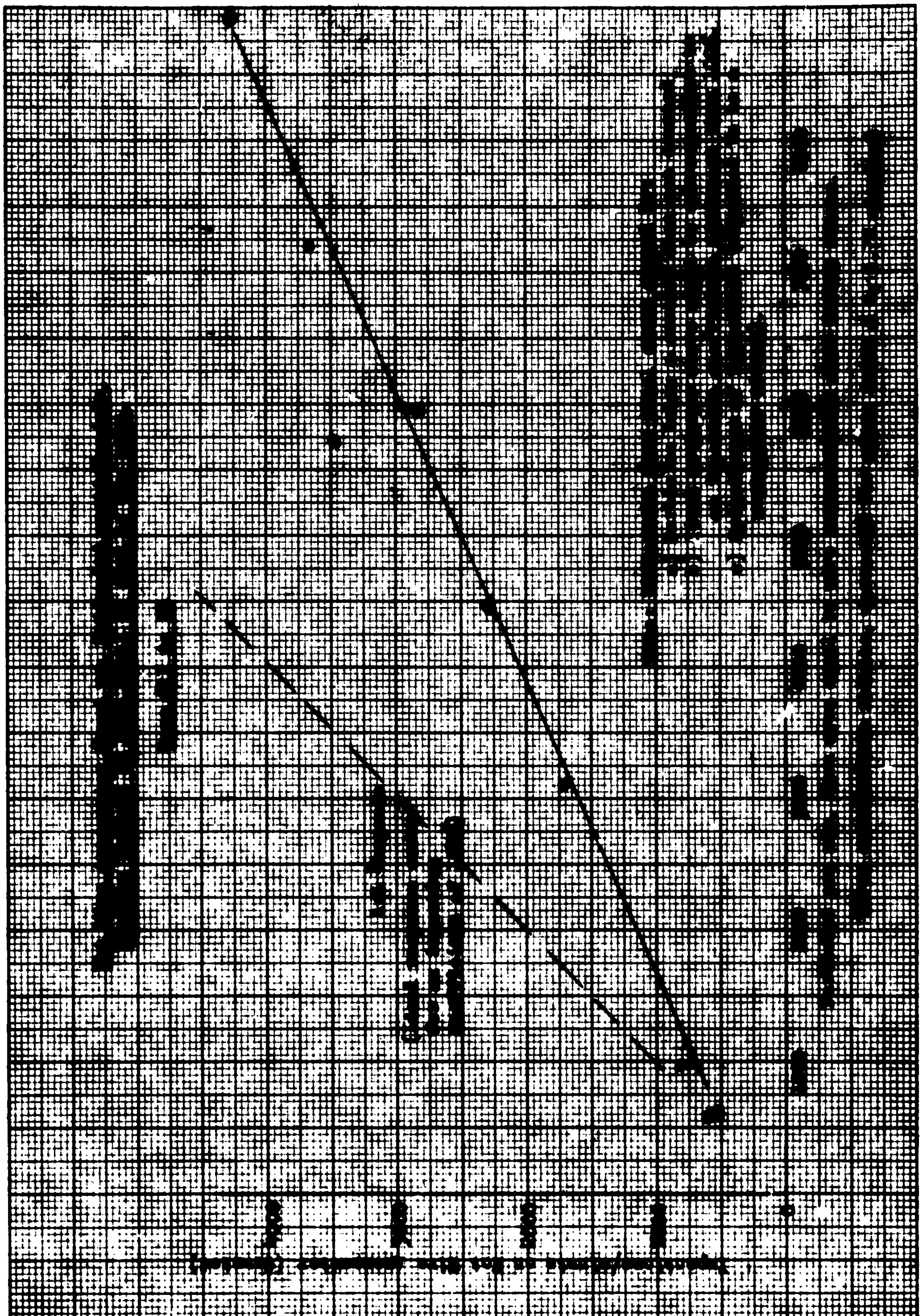


Fig. 18

AD ______________ Assesion No. ______________

Syracuse University, Syracuse, N. Y.

THE SAMPLING OF AEROSOLS IN A TURBULENT AIR FLOW

Progress Report 6, submitted by V. Goldschmidt

The application of the hot wire anemometer as a sampling device for DBP aerosol was found reliable. The count obtained by particles impacting on the heated filament showed a direct correlation to concentrations measured by two other means. A discussion on the coincidence of impactions sensitivity of the response to impactions and a perturbation on the equations of motion for an aerosol in air (obtaining the Reynold's type of equations) are presented.

UNCLASSIFIED

1. Contract No. DA-CML-18-108-61-G-27
2. Sampling
3. Hot Wire Anemometer

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